

# UNITED STATES PATENT APPLICATION

## TITLE:

POROUS, LUBRICATED MIXING TUBE FOR ABRASIVE, FLUID JET

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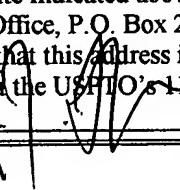
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1           POROUS, LUBRICATED MIXING TUBE FOR ABRASIVE, FLUID JET

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BACKGROUND OF THE INVENTION

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18       1. FIELD OF THE INVENTION

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This invention relates to fluent abrading processes and apparatus. More particularly, this invention relates to an improved mixing or focusing tube for a high speed, abrasive, fluid jet cutting apparatus.

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24       2. DESCRIPTION OF THE RELATED ART

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Cutting with water is a well-known technology that has been prevalent since the 1970's. Water jet cutting is one of a number of technologies known as power beams. These include laser cutting, plasma arc cutting and oxy-acetylene gas cutting.

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By utilizing a high-pressure pump to pressurize water to ultra high pressures and then forcing the water to flow through a tiny orifice can result in water jets that have velocities that are up to three times the velocity of sound. Such a focused water jet has sufficient kinetic energy to cut through most hard-to-cut materials, and when

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1 abrasives are mixed with the water flow so as to yield an abrasive water jet, one can  
2 efficiently cut almost any type of material.

3 Because of their greater cutting power, abrasive water jets account for nearly  
4 60% of the water jet cutting market. Typical applications include the cutting tasks  
5 associated with fabrication of structures using extremely hard materials, such as  
6 titanium and the super-alloys, and in various mining and drilling applications where  
7 hard rocks must be cut. Meanwhile, plain water jets are used for industrial cleaning,  
8 surface preparation and paint stripping applications, and for the cutting of food  
9 products, paper and plastic materials, and woven (e.g., carpet) and nonwoven (e.g.,  
10 filtration materials) products. Saline, water cutting jets have also been used in  
11 medical applications.

12 The primary equipment associated with a typical, abrasive water jet cutting  
13 system is shown in FIG. 1. It consists of an incoming water treatment system, a  
14 booster pump for optimal operation of downstream filters, an intensifier pump that  
15 raises the water's pressure to ultrahigh levels, high pressure plumbing that delivers  
16 the ultrahigh pressure water to the system's cutting head, an abrasive feeder system  
17 that supplies the abrasive particles that are mixed with the ultrahigh pressure water in  
18 the cutting head, and an outgoing water catcher and treatment system.

19 The typical cutting head for an abrasive water jet is shown in FIG. 2. A  
20 sapphire, diamond or ruby orifice is used as the initial orifice to create a high velocity  
21 water jet. The typical diameter of such orifices is 0.07-0.7 mm. A dry abrasive, such  
22 as garnet, silica or alumina (with typical particle sizes being 125-180 microns), is  
23 aspirated/entrained into the mixing chamber by the vacuum created by the water jet.  
24 It mixes with the water jet and the mixed slurry jet is then collimated by a mixing  
25 tube (also called a focusing tube) before exiting the cutting head through the mixing  
26 tube's exit orifice. The diameters of the passages through such mixing tube are 0.5-3  
27 mm, with tube lengths of 50-150 mm.

28 The most troublesome difficulty associated with abrasive water jets, which  
29 presently limits their usefulness, is wear and erosion of the mixing tube walls. Since  
30 the water jet's speed ranges between 100-500 m/sec, and the abrasive particle size can

1 be as high as 40% of the mixing tube's diameter, the mixing tubes must be replaced  
2 frequently, sometimes only a matter of hours.

3 Additionally, the wear of the mixing tube walls leads to the jet becoming  
4 incoherent, which causes an increase in the width of the cut (kerf) on the workpiece  
5 being cut by the jet, deterioration of cutting surface quality and loss of cutting  
6 accuracy. Hence, wear of the mixing tube walls requires constant maintenance and  
7 inspection, which leads to machine down time and increase in the operational costs of  
8 such systems.

9 FIG. 3 presents a schematic representation of the phenomena associated with  
10 wear of a mixing tube. Impact erosion phenomena is thought to dominate the wear in  
11 the initial portion of the mixing tube as the abrasive particles impact on the walls of  
12 the mixing tube at different impact angles. Further downstream the abrasive particles  
13 tend to travel parallel to the walls of the tube and the wear mode tends to change from  
14 impact erosion to sliding, abrasion erosion.

15 Present attempts to solve this wear problem include: (a) the use of mixing  
16 tubes made of very hard materials (e.g., composite tungsten carbide), (b) modifying  
17 the jet's flow structure by using an annular water jet and introducing the abrasives  
18 through a central pipe in an attempt to keep the abrasives away from the mixing  
19 tube's walls, (c) modifying the jet's flow structure by introducing the abrasives  
20 through a central pipe and having the pressurized water enter from radially inwardly  
21 directed ports whose flows combine to create a jet slurry that is focused in the mixing  
22 tube, (d) using a central deflector body prior to the mixing tube so as to create a  
23 downstream wake that helps in entraining the abrasives in the core of the water jet, (e)  
24 using abrasives that are softer than the walls of the mixing tube, and (f) attempting to  
25 configure the general shape of the mixing tube so as to minimize its wear.

26 All of the presently available techniques to reduce mixing tube wear have  
27 major deficiencies. The very hard materials used for mixing tubes are expensive.  
28 Modification to the jet flow structure by introducing secondary flow phenomena is  
29 useful only with relatively slow flows and small abrasive particles; such modification  
30 also causes jet expansion and secondary flow phenomena that limit one's capability to

1 control the cutting process. The use of abrasive particles softer than the mixing  
2 tube's walls reduces cutting efficiency.

3 Thus, despite extensive development efforts to reduce wear in the mixing tube  
4 of a cutting jet, there exists a continuing need for further improvements in this area.  
5 The present invention provides such an improvement.

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## SUMMARY OF THE INVENTION

20  
21 Recognizing the need for the development of an improved mixing tube which  
22 would have greater resistance to being worn away by the abrasive slurry mixtures  
23 flowing through them, the present invention is generally directed to satisfying the  
24 needs set forth above and overcoming the disadvantages identified with prior art  
25 devices.

26 In accordance with one preferred embodiment of the present invention, the  
27 foregoing need can be satisfied by providing an abrasive, fluid jet cutting apparatus  
28 comprising: (a) a chamber having an inlet through which a pressurized fluid jet enters  
29 the chamber, the chamber also having a port through which abrasive particles are  
30 drawn and entrained into the fluid jet, the chamber also having an exit through which  
31 the fluid jet and entrained abrasive particles exit the first chamber, (b) a mixing tube

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1 that is defined at least in part by a perimeter wall, a tube entry port and a tube exit  
2 orifice, the tube entry port being proximate the exit of the first chamber, with the  
3 fluid jet and entrained abrasive particles being mixed in the mixing tube so as to form  
4 a focused cutting jet which exits the mixing tube through its exit orifice, (c) wherein  
5 at least a portion of the mixing tube wall being porous, (d) a lubricating fluid  
6 reservoir that surrounds at least a portion of the mixing tube having the porous wall,  
7 and (e) wherein the lubricating fluid passes from the lubricating reservoir and through  
8 the porous wall to lubricate at least a portion of the surface of the mixing tube wall so  
9 as to resist erosion of the tube wall while the fluid jet and entrained abrasive particles  
10 pass through and exit from the mixing tube.

11 According to a second embodiment of the present invention, a method is  
12 provided for reducing wear in a cutting jet mixing tube due to an abrasive fluid  
13 flowing through the tube. The method comprises the steps of: (a) forming the mixing  
14 tube so that at least a portion of its wall is porous, (b) surrounding at least a portion of  
15 the outer wall of the mixing tube wall with a lubricating fluid reservoir, and (c)  
16 forcing lubricating fluid to pass from the lubricating reservoir and through the porous  
17 wall to form a lubricating film between the mixing tube wall and the flow of the  
18 abrasive fluid.

19 There has been summarized above, rather broadly, the more important  
20 features of the present invention in order that the detailed description that follows  
21 may be better understood and appreciated. In this regard, it is instructive to also  
22 consider the objectives of the present invention.

23 Thus, it is an object of the present invention to provide an abrasive, fluid jet  
24 cutting apparatus, and its method of construction and operation, that reduces the wear  
25 and erosion problems experienced in the cutting jet's mixing tube.

26 It is another object of the present invention to provide a mixing tube apparatus  
27 than can replace the mixing tubes currently used in abrasive, fluid jet cutting  
28 apparatus so as to minimize the wear and erosion problems associated with such  
29 tubes.

1 It is another object of the present invention to provide an abrasive, fluid jet  
2 cutting apparatus and its method of construction and operation that will expand the  
3 usefulness of such jet cutters by increasing the precision and efficiency of their cuts.

4 It is yet another object of the present invention to provide an abrasive, fluid jet  
5 cutting apparatus and its method of construction and operation that will expand the  
6 range of applications of such jet cutters.

7 It is a further object of the present invention to provide a method and device  
8 for abrasive cutting that will increase the cost effectiveness of such cutting processes.

9 These and other objects and advantages of the present invention will become  
10 readily apparent as the invention is better understood by reference to the accompanying  
11 drawings and the detailed description that follows.

12 Thus, there has been summarized above, rather broadly, the more important  
13 features and objectives of the present invention in order that the detailed description  
14 that follows may be better understood and appreciated. There are, of course,  
15 additional features of the invention that will be described hereinafter and which will  
16 form the subject matter of any eventual claims to this invention.

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24 **BRIEF DESCRIPTION OF THE DRAWINGS**

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26 FIG. 1 is a schematic representation of the components of a typical abrasive  
27 water jet cutting system.

28 FIG. 2 is a cross-sectional view of the typical cutting head in an abrasive water  
29 jet cutting system.

30 FIG. 3 is schematic representation that illustrates the phenomena associated  
31 with wear and erosion of the walls of a mixing tube.

1 FIG. 4 is a cross-sectional view of a preferred embodiment of an abrasive water  
2 jet cutting apparatus of the present invention  
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13 **DESCRIPTION OF THE PREFERRED EMBODIMENT**  
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15 Before explaining at least one embodiment of the present invention in detail,  
16 it is to be understood that the invention is not limited in its application to the details  
17 of construction and to the arrangements of the components set forth in the following  
18 description or illustrated in the drawings. The invention is capable of other  
19 embodiments and of being practiced and carried out in various ways. Also, it is to be  
20 understood that the phraseology and terminology employed herein are for the purpose  
21 of description and should not be regarded as limiting.

22 Referring now to the drawings wherein are shown preferred embodiments and  
23 wherein like reference numerals designate like elements throughout, there is shown in  
24 FIG. 4 an abrasive water jet cutting apparatus 1 of the present invention. It consists  
25 of a chamber 10 having an inlet orifice 12 through which a high pressure (50 - 600  
26 MPa or 7.5 - 90 kpsi), water jet enters the chamber.

27 The water jet flows through the chamber 10 and entrains abrasive particles  
28 that are fed at low pressure through a port 14 in the chamber's sidewall. The abrasive  
29 particles combine with the water jet to form a slurry jet that flows from the chamber's  
30 exit 16 and enters the entry port 18 of the apparatus' focusing or mixing tube 20.

1 As shown in FIG. 4, this embodiment utilizes a mixing tube 20 that is  
2 constructed from a porous rod through which a central bore has been either machined  
3 or cast, thereby resulting in the mixing tube having a perimeter wall 22 that is porous  
4 and an exit orifice 24 through which the slurry jet exits the mixing tube 20. The outer  
5 wall 26 of the mixing tube is surrounded by an oil or lubricating fluid reservoir 28.

6 The lubricating fluid reservoir 28 is pressurized so that the lubricating fluid is  
7 forced through the porous wall to create a thin film of lubricant on the walls of the  
8 mixing tube 20 that serves to protect them from the wear and erosion caused by the  
9 passage of the abrasive particles through the tube.

10 It should be appreciated that the cross sectional form of the jet that exits the  
11 mixing tube can be configured to give a variety of shapes by appropriately configuring  
12 the cross sectional shape of the mixing tube. For example, the use of a round passage  
13 through the mixing tube will yield a round cutting jet, whereas the use of an oval  
14 passage thorough the mixing tube would yield an oval cutting jet. All of these various,  
15 possible cross sectional shapes are considered to be within the scope of the present  
16 invention.

17 In use, the pressure in the lubricating fluid reservoir is higher than the  
18 pressure in the mixing tube 20. Since the lubricant is constantly replenished from the  
19 lubricant reservoir 28, sites where abrasive particles "gouge" the lubricant's  
20 protective film are "repaired", reducing or preventing damage to the tube's walls.  
21 The thickness of the lubricating film is designed to prevent contact (impact) between  
22 the particles in the slurry jet and the inner or perimeter wall of the mixing tube and to  
23 prevent the high loading stresses on the wall that could lead to its erosion.

24 An approximated analysis to determine the required thickness of the lubricant  
25 layer indicates, for example, that an approximately 10-20 micron thick layer of oil is  
26 sufficient to prevent contact between the abrasive particles and the tube wall for a  
27 500 micron diameter, 200 m/sec slurry jet containing 150 micron diameter abrasive  
28 particles having a specific gravity of 4 and where the jet fluid is water. For this  
29 example, the lubricant's kinematic viscosity should be about 1000 times that of water  
30 (at 25°C). In general, the required thickness of the lubricating film is dependent on  
31 the flow conditions, including slurry velocity, mixing tube geometry, abrasive

1 particle specific gravity, shape and void fraction, as well as the viscosity of the  
2 lubricating fluid. In most cases, the lubricant film thickness need be only a few  
3 percent (about 0.5-6%) of the mixing tube's diameter.

4 Due to the differences in viscosity between the fluid and the lubricant  
5 (typically 100-40,000:1 if oil is used as the lubricant and water is used as the carrier  
6 fluid, at 25°C), and the thinness of the lubricant film, the lubricant flow rate can be  
7 kept at a very low level (characteristically, below 1-5% of the carrier fluid flux, and  
8 in some cases even as low as 0.01%). Thus, lubricant consumption is relatively  
9 minimal.

10 The lubricant can be of any desired type, so long as the lubricant creates a  
11 protective film on the inner wall of the mixing tube 20. Use of liquid polymers  
12 provides an additional advantage in situations involving high shear strains ( $>10^7$ ) like  
13 those occurring in the mixing tube 20, since liquid polymers tend to "harden" under  
14 such conditions (that is, become less of a viscous material and more of a plastic  
15 solid). Thus, liquid polymers can absorb much more energy and stresses from  
16 laterally moving abrasive particles. Synthetic, light lubricants (such as poly alfa  
17 olefins) that can be easily drawn or forced through a porous medium should provide  
18 some level of protection to the walls of the mixing tube 20 under low flow  
19 conditions. In general, prevention of wear and erosion in the mixing tube 20  
20 improves with increasing lubricating fluid viscosity and with increasing lubricating  
21 fluid flow rates.

22 In the preferred embodiment, the lubricant reservoir 28 and the fluid cutting  
23 jet are pressurized from the same source. Due to the high speed flow of the slurry  
24 through the mixing tube 20 and the almost stagnant fluid pool in the lubricant  
25 reservoir 28, a pressure difference exists between the inner and outer sides of the  
26 porous wall of the mixing tube 20 that is generally sufficient to draw the lubricant  
27 through the porous wall. The lubricant reservoir 28 can also be pressurized by a  
28 separate pump if need be to obtain higher lubricating fluid flow rates.

29 The mixing tube 20 can be made from a wide range of porous materials, but is  
30 preferably made of a hard, moldable or easily machined, porous material. The tube's  
31 pore size or its wall thickness can be varied to provide for different lubricant flow

1       rates. Nominal pore sizes of 0.2-20 microns have been found to work well in this  
2       application. Further, the mixing tube 20 need not be made completely of porous  
3       material. For example, a porous ring could be used upstream from a non-porous,  
4       mixing tube exit tip to provide enough lubrication along the inner surface of the tip to  
5       substantially reduce its erosion. In a different configuration, the porous ring can be  
6       downstream of a non-porous portion, where wear would be greatest. Alternatively, a  
7       mixing tube can be configured with stacked multiple porous and non-porous rings.  
8       As another alternative, a mixing tube can be configured with stacked multiple porous  
9       rings having different lubricant flow rates (for example, due to different porosity or  
10      thicknesses).

11      Moreover, while a uniformly porous material is preferred for the mixing tube  
12      20, in an alternative embodiment, a number of very fine to extremely fine holes can  
13      be bored (such as by a laser drill) through a mixing tube formed of non-porous  
14      material to make the tube effectively porous.

15      Various experiments were undertaken to identify the optimal porous material  
16      for this application. It was found that gravity sintered materials were more useful in  
17      this application than materials made by pressure compaction followed by sintering.  
18      This was due to the fact that porous materials are susceptible to "smearing or  
19      blocking" of the pores during their machining for this application, even when using  
20      Electric Discharge Machining (EDM). Repeated machining experiments of various  
21      nominal pore sizes in the range of 0.2-20 microns showed that EDM of the gravity  
22      sintered material, at optimized EDM operating parameters (see below), yielded  
23      considerably less smearing than with the pressure compacted, porous materials.

24      The optimal EDM operating parameters for fabricating the gravity sintered,  
25      porous materials utilized low cutting speeds, low energy levels and low spark  
26      frequencies with Wire EDM. For example, fabrication of porous, 316-stainless steel,  
27      mixing tubes with little smearing can be achieved by utilizing the following EDM  
28      parameters: cutting speed = 0.38 mm/minute, spark cycle = 30  $\mu$ sec, wire diameter =  
29      0.25 mm brass, with the other parameters being specific to the machine used (i.e.,  
30      spark energy = 20% of max., wire speed = 20% of max., wire tension = 80% of max.,  
31      and water conductivity = 67% of max.). After machining, the mixing tubes are

1 submerged in a liquid that vaporizes easily, such as methanol, and cleaned using  
2 ultrasonic cleaning to remove debris and carbon particles generated during the  
3 machining.

4 As an alternative to machining a gravity sintered, porous material, one may  
5 elect to use a porous ceramic material and cast this material in such a manner that the  
6 passage connecting a mixing tube's inlet and outlet ports is formed in the original  
7 casting of the tube.

8 The lubricant injection rate is controlled by the pressure difference across the  
9 wall of the mixing tube 20, the lubricant viscosity, porous medium permeability, and  
10 the thickness of the mixing tube wall. The pressure within the mixing tube 20 is not  
11 constant due to the change in slurry's velocity resulting from changes in cross-  
12 sectional area of the mixing tube 20 and due to shear stresses along the perimeter  
13 wall of the mixing tube 20 nozzle. To insure a desirable lubricant flow rate at every  
14 point, the thickness of the porous walls of the mixing tube 20 can be varied. The  
15 exact shape of the mixing tube 20 can be determined by solving the equations of  
16 motion for fluid flow in the porous medium with the prescribed flow rate at every  
17 point as a boundary condition. Thus, it is possible to prescribe a relatively exact  
18 injection rate.

19 The operating efficiency of these porous mixing tubes was found to be  
20 considerably increased by filtering the lubricating fluid prior to its injection through  
21 the porous material. Without such filtering, the porous material is very prone to  
22 become clogged with debris found in the lubricating fluid. Pieces of this same porous  
23 material were used to filter the lubricating fluid.

24 With lubricated walls, the diameter of the mixing tube 20 can be substantially  
25 decreased to sizes that are only slightly larger than the diameter of the abrasive  
26 particle. For example, if the maximum particle diameter is about 150 microns, the  
27 mixing tube diameter can, in principle, be reduced to about 300 microns, including  
28 the oil film. Typical tube diameters are in the range of three times the diameter of the  
29 chamber's inlet orifice, or on the order of 50-3,000 microns. A smaller mixing tube  
30 diameter provides sharper and more precise cuts with less material loss from a  
31 workpiece. As a further consequence of lubricating the mixing tube walls exposed to

1       the slurry, the slurry velocity can be increased to considerably higher speeds without  
2       damage to the tube's walls, thereby increasing the abrasive power of the slurry and  
3       the cutting efficiency of the system.

4       Although the preferred embodiment of the invention uses liquid as the carrier  
5       fluid, the carrier fluid can be a gas or liquid/gas mixture. Further, while the preferred  
6       embodiment uses abrasive particles as the principal cutting material, the lubricated  
7       mixing tube 20 of the present invention should also reduce wear due to cavitation  
8       when used with only highly pressurized cutting liquid. Thus, "abrasive fluid" or  
9       "cutting fluid" should be understood to include fluids with or without entrained  
10      abrasive particles.

11      Although the foregoing disclosure relates to preferred embodiments of the  
12      invention, it is understood that these details have been given for the purposes of  
13      clarification only. Various changes and modifications of the invention will be  
14      apparent, to one having ordinary skill in the art, without departing from the spirit and  
15      scope of the invention as hereinafter set forth in the claims.

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